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Le Roi Soleil
by Piero Fornasetti

MAGNETIC FIELDS AND DYNAMICS
OF THE SOLAR ATMOSPHERE

BY

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MAGNETIC FIELDS AND DYNAMICS OF THE SOLAR ATMOSPHERE,

being an introduction to and a summary of the following articles:

- I. D.Dravins: Magnetic Field and Electric Current Structure in the Chromosphere, Solar Physics, in press, 1974
- II. D.Dravins: A Possible Solar Electrograph, Astrophysical Letters, vol. 13, 243, 1973
- III. D.Dravins: Evolution of Structures in the Bright H α Network, in R.G. Athay (ed.): Chromospheric Fine Structure, IAU symposium No. 56, p.180, 1974
- IV. D.Dravins: Horizontal Velocities in the Solar Photosphere, submitted to Solar Physics, 1974

Solar magnetic fields strongly influence the dynamics of the gases in the solar atmosphere and especially so in active regions where the matter often seems to follow magnetic fieldlines and where violent eruptions can take place in regions of particularly complex magnetic field patterns. Conversely, gas motions strongly influence the magnetic field structure. In supergranular cells, horizontal flows in the photosphere sweep the magnetic fieldlines to the cell perimeters, where the field concentrations contribute to the locally higher temperatures and outline the loci of spicules, gas jets that rise up into the chromosphere.

This work investigates various aspects of magnetic- and velocity fields in the solar atmosphere and their interplay. Papers I and II deal with the determination of magnetic flux density, electric current density and electric field in the chromosphere of an active region, while papers III and IV mainly concern themselves with studies of velocity fields. The individual papers are summarized below.

I. MAGNETIC FIELD AND ELECTRIC CURRENT STRUCTURE IN THE CHROMOSPHERE

As you will agree, an active region on the Sun is a beautiful one with all its spectacular events in photosphere, chromosphere and corona. A challenge to the optical observer, a unique and inexhaustible paradise for the investigator of the interplay of magnetic fields, turbulence, hydromagnetics and radiation in a stellar plasma!

K.O.Kiepenheuer
IAU Symp.No.35, p.4 (1968)

... we must find a Rosetta stone in the form of a high quality pair of magnetogram and filtergram. This problem is particularly difficult in active regions, where field patterns are particularly complex.

Harold Zirin
IAU Symp.No.43, p.237 (1971)

Janssen in 1869 suggested that a monochromatic image of the chromosphere could be achieved with a spectrograph by moving two slits in tandem and during the early 1890's the first spectroheliographs came into operation. When red-sensitive photographic plates became available and the first spectroheliograms in the hydrogen H α line were obtained at Mt. Wilson in 1908, the swirling structure of chromospheric features in active regions became apparent. Their close correlation with regions of strong magnetic fields around sunspots was soon realized and in 1913 Hale wrote that "The resemblance of the structure near bipolar groups to the lines of force about a bar magnet is very striking."

Since that time, the evidence has been steadily growing that these H α features, now known as fibrils, indeed do outline magnetic lines of force. However, no direct confirmation has been possible, because available techniques do not yet allow reliable measurements of vector magnetic fields inside and outside of discrete fibrils. Observations near the limb are difficult, because of overlapping and crowding of features along the line of sight, and observations near disk center are difficult, because of lack of suitable spectral lines whose range of formation is confined to a region inside the fibril. Possibly, the situation will improve with the advent of high resolution magnetographs for the far ultraviolet.

Many events in the solar atmosphere are governed by electromagnetic fields, and in order to gain further insight in these, one needs information on the field structure. Solar magnetographs generally record only the longitudinal field, i.e. the component along the line of sight, and since the records are usually made in only one photospheric spectral line, the

information is further limited to a two-dimensional surface on the sun. However, to describe the electromagnetic fields one needs information not only on all components of the magnetic flux density vector $\underline{B}$ but also on the electric current density vector $\underline{j}$ and in 3 dimensions throughout the atmosphere. In order to obtain the 3-dimensional magnetic field structure, a great amount of effort has been made during the last decade designing various theoretical models that fulfil the border conditions at the photosphere set by the observed fields there. To limit the computing effort, some simplifying assumptions have to be made. A commonly used one (and the simplest) is that of a "current-free" field, i.e. assuming the electric current density everywhere $= 0$. This is equivalent to assuming a vacuum above the solar surface and the field arising from magnetic dipoles or monopoles distributed on or inside the solar surface. The fieldlines are then integrated for larger heights above the photosphere. It is argued that, for example, following large flares, the chromosphere should be locally "swept clean" and the freshly rearranged fieldlines be similar to current-free ones. Another commonly used assumption is that of a "force-free" field, i.e. assuming the electromagnetic Lorentz-force $\underline{F} = \underline{j} \times \underline{B}$ everywhere $= 0$. Thus, currents are allowed to circulate, but are restricted to always being parallel to $\underline{B}$; $\underline{j} = \underline{\text{curl}} \underline{B} / \mu_0 = \alpha \cdot \underline{B}$, where the scalar function α is freely chosen. This is equivalent to assuming the atmosphere in static equilibrium and neglecting gravity and pressure forces. It is argued that since the magnetic energy density in the chromosphere exceeds the kinetic energy density, the magnetic forces should rapidly achieve a static equilibrium. The success of these models is usually judged on the degree of similarity that is obtained with observed Ha structures in active regions: it is implicitly assumed that these follow magnetic fieldlines.

With specially designed vector magnetographs it is possible to observe the full vector magnetic field and to obtain a height dependence by repeating the observations in different spectral lines. By differentiation one may also obtain the electric current density. Such observations are difficult to carry out but the few that have been made have all cast some doubts on the validity of the theoretical models.

Paper I is investigating the properties of the magnetic field, which is deduced by explicitly assuming that fibrils outline magnetic fieldlines. The aim is to determine the full 3-dimensional vector magnetic field structure in the chromosphere above an active region, using observational data only and without any theoretical assumptions on the nature of the field. No such treatment has been made before.

The work is begun by selecting an active region suitable for investigation. This should be observed near the center of the disk and be not too complex. The most important requirement is the availability of a simultaneous digital magnetogram. A large size enlargement of the H α photo of this active region was mounted on a board and the magnetogram superposed. Next, 400 metal wires, representing magnetic fieldlines were mounted with a number density proportional to the local flux-density. These were bent over, following the H α structures and reconnected to the regions of opposite polarity. The whole model was digitized and the field-line coordinates used to retrieve the 3-dimensional vector magnetic-field matrix with about 3,000 points in space. The electric current-density vector $\underline{j}$ is calculated from $\underline{j} = \underline{\text{curl}} \underline{B} / \mu_0$ and the electromagnetic Lorentz-force from $\underline{F} = \underline{j} \times \underline{B}$.

It was found that there are considerable electric currents (average magnitude 10^{-2} A/m^2) circulating in the active region. The currents are mainly horizontal (surface currents on the sun), they are tracing out large scale structures, that are different from the magnetic field structures, and the currents are not at all parallel to $\underline{B}$. This is in agreement with vector magnetograph data but disagrees with theoretical force-free and current-free models. The Lorentz-force structures, however, do correspond to observed chromospheric structures. In all bipolar regions, there is a systematic downward force in the lower chromosphere and a systematic downward motion may be predicted. Such a motion is actually observed. In the upper chromosphere, the force changes sign and becomes directed radially outward. It is stronger than gravity, and matter should generally be streaming outward from the upper chromosphere into the corona. This is a consequence from the fact that magnetic flux on the sun is erupting in bipolar flux-loops. Especially strong radially outward streams are predicted above strong bipolar regions. This is where coronal streamers are always observed.

The main conclusion is that existing observations are consistent with a dynamic, non force-free, non current-free chromosphere with electromagnetic forces in action. If this conclusion is correct, the interpretation of several chromospheric phenomena will have to be reconsidered: not only magnetic-field models but also models of, for example, fibrils, where dynamic models (like a shock wave propagating along magnetic tubes of force) may have to be preferred over static models (like a cloud lying in pressure equilibrium).

II. A POSSIBLE SOLAR ELECTROGRAPH

*At the chromospheric level
Much is seen that plagues the devil
For there is the nimbus queer
Which with great flares may appear.
Is it just an obscuration
Or a subtler manifestation
Of magnetic changes?*

J.H.Reid
Irish Astron.Journ.8, 67 (1967)

Solar flares are the most energetic events in the solar system. They have been studied with a huge variety of instruments ranging from radio telescopes to high-energy particle detectors. What is observed, however, are only secondary effects, such as H α brightening, radio bursts, mass motions, etc. The underlying process that triggers the instability where more than 10^{25} Joule may be released in merely a minute, is not at all understood and remains unobserved.

Observations have given indications of considerable electric currents flowing in active regions. In flare theories this has been taken into account, since current disruption due to changes in the solar plasma electric conductivity might explain the energy release with the up to 30 GeV solar protons observed from flares. Such theories predict strong transient electric fields in connection with the pre-flare processes: possibly more than 10^{10} Volts. Other flare theories that invoke rapid magnetic field annihilation also lead to potential differences up to 10^{10} V. In paper II an attempt to observe such a pre-flare energy buildup is described.

In external electric fields certain spectral lines split up into differently polarized components due to the Stark effect. Stark broadening of spectral lines due to microscopic, statistically fluctuating fields caused by discrete electrons, is well known in astrophysics but astronomical observations of Stark splitting have never been made. The Stark splitting is generally more complex than the analogous Zeeman splitting in magnetic fields and only very few spectral lines exist that might be usable for the sun. Of these, the hydrogen H α line was selected and a search for possible transient electric fields in active regions initiated. The search principle was that, in the presence of an electric field, the line will exhibit a net linear polarization in any small part of the line profile.

At Big Bear Solar Observatory, the videomagnetograph system was converted to an "electrograph" mode. An active region was photographed on a video tube through a narrow bandpass H α filter and a linear polarizer. The video picture was read out and stored on a magnetic disk and a new frame obtained with the polarizer rotated 90 $^{\circ}$. This was then subtracted from the first frame, thus yielding an analog map of the linear polarization. To improve the signal/noise ratio, this process was repeated a few hundred times and the averaged picture displayed on a TV screen where it was photographed. One such linear-polarization map was obtained every 30 seconds.

The large active region of August 1972 was followed for some time and the development of a few medium size flares covered. However, the search for transient polarization changes revealed nothing above the noise level.

III. EVOLUTION OF STRUCTURES IN THE BRIGHT H α NETWORK

... the chromospheric network is the site of enhanced vertical magnetic fields, downward-flowing material, and locally higher temperatures. ... All of these seemingly diverse phenomena can be assembled into a coherent picture if we regard the dynamics of the photosphere as the primary driving mechanism and the solar magnetic field as a means of coupling these dynamics to the density and temperature nonuniformities; hence to the emission nonuniformities of the chromosphere.

Edward G. Gibson
'The Quiet Sun', p.229 (1973)

The network on the quiet sun is formed by the perimeters of the super-granulation cells. These are about 30,000 km in diameter (much larger than granules) and have a regular velocity-pattern such that matter flows outward towards the perimeter, where it sinks down.

During 1972, Dunn and Zirker at Sacramento Peak Observatory succeeded in obtaining white-light photographs of this network near the center of the solar disk. It shows up as an extremely tiny (about 0.2 arcseconds), bright lacework intermingled between the photospheric granules, which prompted them to suggest the name "solar filigree". A prerequisite for observing the filigree is outstanding seeing conditions - they had not been seen before, even on granule photographs obtained from stratospheric balloons.

Soon thereafter, the work described in paper III was initiated with the aim to study the time evolution of the filigree. As the Sacramento Peak data had shown, they could also be seen on H α filtergrams taken far out in the line wing. This H α radiation comes from higher layers in the atmosphere than the continuum, and here the filigree appear coarser (≈ 0.5 arcsec), enough so to be resolvable also with moderate size telescopes. An H α patrol had been operated with the two 25-cm telescopes at Big Bear for a few years, with typically one photograph taken every 10 seconds. This very large quantity of data (about 10^5 frames on 2 km of film) was examined to search for possible frames taken during moments of extraordinary seeing-conditions. Since it is very difficult to see the filigree clearly on the original 35 mm film, some 1,000 paper-prints and some 500 sheet-films were made. Finally, some sequences were found where, at moments, the resolution seemed to be only diffraction-limited. These were selected to undergo spatial filtering with a coherent-light processor.

The aim was to enhance the very high spatial frequencies and thus to bring out more detail in the small filigree structures. This process, however, failed to improve the images, the main reason being that the size of the filigree is not very much larger than the film grain size and the latter's spatial spectrum still has considerable power at filigree frequencies and cannot be filtered out.

The frames that were finally presented have somewhat lower spatial resolution than the Sacramento Peak data but do cover a much longer timebase, 26 hours. The time evolution over this period was then studied.

It was found that the gross filigree network evolves on a time-scale of about 20 hours, while the tiny structures evolve on time-scales of about 10 minutes. The former value is close to the lifetime of supergranulation cells, while the latter is close to the lifetime of individual granules. Very notable is the fact that the total area taken up by the bright elements in the network does not change markedly over shorter time-scales. This indicates that the features are the same ones who have just moved, their proper motions reflecting the evolving granules. If this interpretation is correct, then one has, for the first time, access to tracer structures, which can be followed to infer the horizontal velocity field.

When comparing filigree photos taken in the blue and the red wings of the H α line, one notes that the features are brighter and more prominent in the blue wing. This is contrary to what one would expect from a naive model where the matter at supergranule boundaries is drifting downwards (and thus red-shifted). The hypothesis is expressed that this can be interpreted as the gases sliding down on both sides of the bright structures. These gases will be red-shifted and cause a heavier obscuration of the filigree in the red wing. If, in addition, the bright elements are identified with the locations of strong vertical magnetic fields, these assume the role of a wall standing up between two adjacent supergranules.

IV. HORIZONTAL VELOCITIES IN THE SOLAR PHOTOSPHERE

... for the Sun, our knowledge of even the most basic properties of the micro- and macroturbulence is in a state of almost total confusion. We have not been able as yet, for example, to decide whether within the photosphere the microturbulence is isotropic and increasing outwards or anisotropic and decreasing outwards. ... In the case of macroturbulence we are perhaps even less certain of the characteristics of motion.

R. Grant Athay

'Radiation Transport in Spectral Lines', p.131 (1972)

The solar atmosphere, also in its "quiet" regions, is in a state of perpetual motion. One method to study small-scale velocities is to obtain high spatial resolution, high dispersion spectrograms, where individual turbulence elements can be resolved. The different Doppler shifts of adjacent elements cause a wiggly appearance of the spectral line. Such spectrograms can only be obtained during very good seeing conditions, again emphasizing the fundamental need for high spatial resolution in solar research. Almost all such studies so far have concerned themselves with the vertical velocities which are more easily observed since they give rise to Doppler shifts at solar disk center, while horizontal velocities do not. Those few who have considered also horizontal velocities have done so without regarding the fact that the curvature of the solar surface and the change of both the average formation height of the spectral line and its formation-height range, at positions away from disk center, may give fortuitous results, unless properly corrected for.

The first part of paper IV deals with the analysis of statistical Doppler shifts as seen in one photospheric spectral line of neutral iron on 4 different spectrograms, covering 4 arcminutes on the sun and reaching the solar limb. Near the limb one is looking nearly tangentially to the solar surface and the contribution to the Doppler shifts then comes largely from the horizontal velocities. The line profiles on each spectrogram were measured for 449 different limb distances with a digital microphotometer and the Doppler displacements calculated. The height of line formation increases monotonically as one goes towards the limb and the actual height values were obtained from available non-LTE calculations for a standard

model-atmosphere. Also the formation-height range, i.e. that height interval in the atmosphere, where the line is formed, changes. This change is different for different parts of the line profile, and the wavelength positions in the line wing that were sampled for Doppler shifts were selected slightly differently for different limb distances, in such a way that the formation range is constant and independent of position on the sun. This is vital since one wishes to make a statistical velocity-analysis for volumes of constant size. To assure this, also the solar surface-area of sampling must be constant. This was achieved by digitally averaging the velocity data over simulated apertures with an angular extension proportional to $\cos \theta$ (θ = heliocentric angle). The root-mean-square velocities as a function of θ were obtained and, using previously known height-variation of vertical velocities (which increase with height), the horizontal rms velocities could be obtained. It was found that from an rms value around 450 m/s for a resolution volume of $800 \times 3,000 \times 250$ km, they decrease rapidly with height. An extrapolation indicates negligible horizontal velocities already at a height of 250 km above the photosphere. This decrease of the macroscopic horizontal velocities with height must be of importance not only for calculations of model-atmospheres, but also for the processes where magnetic fields are swept to supergranule boundaries by horizontal gas flows.

In the second part of the paper, the time evolution of solar filigree is considered, and small elements are used as tracers for the horizontal velocity field, yielding a very high ($\approx 500 \times 500$ km) spatial resolution. The interpretation is made somewhat complicated by the unknown effects of seeing-induced image motion in different frames. Still, it can be concluded that the filigree show proper motions implying average horizontal velocities of about 1 km/s. If these values are typical and randomly distributed (i.e. representing a horizontal macroturbulence), the rms value should decrease as the inverse square root of the sampling area. This area in the spectral line analysis is about 10 times larger and the calculated velocity about 3 times smaller, which is consistent with such an interpretation.

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*Just how can one reconcile
All these facts, without guile.
It looks as if many a sunny day
Will pass along on its way
Before we solve it all.*

J.H.Reid

